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A method for forming three-dimensional objects comprises irradiating with a source (24) an uncured photopolymer (11) by transmitting an effective amount of photopolymer solidifying radiation through a radiation transmittant material (13, 16, and 23) with areas of different opacity (18-22) which leaves the irradiated surface capable of further cross-linking so that when a subsequent portion of solid object (25) is formed it will adhere thereto. In another embodiment other means of preserving subsequent cross-linking are used instead of the transmittant material. Using either method three-dimensional objects (25) can be made layer by layer or point by point.

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METHOD AND APPARATUS FOR PRODUCTION OF THREE-DIMENSIONAL
OBJECTS BY PHOTOSOLIDIFICATION

This invention relates generally to improvements in a method and apparatus for production of three-dimensional objects. More specifically, it relates to a method and apparatus for forming three-dimensional objects by the irradiation of photopolymers that solidify in response to radiation.

All of the commonly practiced processes for fabricating three-dimensional objects have disadvantages. For example, the mechanical removal of material to form such objects involves much energy, time and processing; the chemical machining to form such objects has depth limitations and the incapability of making complex shapes; and the thermal molding requires expensive molds; it is very inflexible and it takes much time and energy.

Several methods and apparatus have been developed for the production of three-dimensional objects by irradiation of photopolymers that cross-link and solidify upon irradiation. Forming three-dimensional objects by solidifying each point individually can be accomplished by scanning the whole volume of the object point by point with intersecting beams. However, such methods are very complex and expensive. The forming of three-dimensional objects by building-up successive extremely thin laminae of the solidified photopolymer involves many production steps due to the large number of laminae required. As a result the system can be time consuming and complex. There also are other drawbacks such as shrinkage distortion of the open irradiated surface.

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Three-dimensional objects of various geometries are widely used everywhere in final products, prototypes and models. A large portion of such objects could be made of photopolymers by photosolidification if there were a
5 suitable apparatus and method of producing these objects which resulted in dramatic reductions in cost and time and improvements in accuracy and performance characteristics.

The primary objects of the present invention are to
10 provide an improved apparatus and method for making three-dimensional objects by the photosolidification of photopolymers.

The preferred method of the present invention for generating three-dimensional objects from a photopolymer
15 capable of solidification in response to radiation comprises providing a quantity of uncured photopolymer in a container. A rigid radiation transmittent plate, which has a bottom coating to which the solidified polymer will not adhere and which does not prevent the
20 further cross-linking of the polymer, is placed in contact with the photopolymer. Next, an effective amount of photopolymer solidifying radiation is then transmitted through the plate into the uncured photopolymer, causing the photopolymer exposed to the light to solidify as a
25 three-dimensional object. The thus obtained object of solidified polymer can be enlarged, if desired, by repeating the procedure, i.e., adding more photopolymer onto the object, repositioning the plate and repeating the irradiation.

30 By applying modulated radiation, complex three-dimensional objects can be formed during each procedure. But, the objects are limited in thickness or accuracy and can have only one layer of cavities.

To form more complex, thicker or more accurate
35 objects, or to avoid the complicated modulation otherwise necessary in some cases, individual slices of an object

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are successively built up one atop of another. This is possible with the method of the present invention because the irradiated surfaces of the solidified photopolymer, which are in contact with the radiation transmittant plate, retain sufficient cross-linking capability after the initial irradiation and each subsequent slice automatically adheres to the preceding one to form combination objects.

Objects of virtually any geometry can be formed point by point or part by part when the radiation transmittant plate is small and scans desired points inside the photopolymer coming into direct contact with them.

The simplest form of the novel apparatus of the present invention includes a container for the uncured photopolymer; relatively rigid transparent plate adapted to rest upon the top surface of the uncured photopolymer, which plate has a bottom surface which does not interfere with the further cross-linking of the polymer and can be removed after irradiation; one or more masks to modulate radiation, which can be a part of the plate or a separate item; and a source of photopolymer solidifying radiation. The preferred apparatus also includes a removable substrate in the container upon which the solidified photopolymer can rest.

In another embodiment of the apparatus an optical fiber of small cross-section is employed as a transparent plate and is adapted to come into contact with any point inside the uncured photopolymer. By scanning the photopolymer point by point, objects of any geometry can be made.

In drawings which illustrate embodiments of the invention:

Fig. 1 is a view, partly in section, of a preferred embodiment of the apparatus of the invention;

Fig. 2 is a similar view of a second embodiment;

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Fig. 3A is a schematic view of a multilayer object formed by the method of the invention;

Fig. 3B is a schematic view of an object formed by one embodiment of my method;

5 Fig. 4A and 4B are schematic views showing the use of a modulating radiation source;

Fig. 5 is a schematic view of an electric circuit board made by the method of the present invention;

10 Fig. 6 is a view of an embodiment useful for automatic fabrication;

Fig. 7 is a view of an embodiment of a radiation guide with a modulating radiation source mounted inside the guide;

15 Fig. 8 is a view, partly in section, of an embodiment for forming point by point and area-by-area;

Fig. 9 is a similar view of radiation guide emitting radiation upwards; and

Fig. 10 is a view of another embodiment (container and drive not shown).

20 The invention will now be described in connection with the drawings.

As seen in Fig. 1, a container 10 is partially filled with an uncured photopolymer 11 that solidifies when irradiated, preferably with ultraviolet (UV) or similar
25 radiation. Secured in the container 10 is a substrate 12. A radiation-transmitting, rigid plate 13 is supported on the top surface of the liquid photopolymer 11 by supports 14, only two of which can be seen. The distance between substrate 12 and plate 13 is equal to
30 the desired thickness (T) of the object to be formed.

The plate 13 covers the top surface of the photopolymer 11 so no air is entrapped between the plate 13 and the top surface of the photopolymer 11. Plate 13 should be rigid enough to provide desired shape for the
35 top surface of the polymer and to keep it unchanged during solidification. Plate 13 should preferably not

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seal the container so that fluid volume changes resulting from solidification are made up by unrestricted supply of fluid from around the irradiated area. Resting on the top surface of the plate 13 is a mask 15 which has transparent areas 16 and areas of different opacity 18, 19, 20, 21 and 22. The bottom of the transparent plate, which is either glass or quartz, has a transparent coating 23 which does not substantially interfere with the ability of the photopolymer to further cross-link and can be removed after irradiation. Positioned above the mask 15 is a source of photopolymer solidifying radiation 24.

When it is desired to make a desired three-dimensional object with the described apparatus, radiation from the light source 24 is transmitted through the mask 15, plate 13 and coating 23 into the uncured photopolymer 11 to selectively solidify it and form a three-dimensional solid object 25 (seen in cross-section) which is adhered or attached to substrate 12.

The more radiant energy which is applied the greater is the depth of solidification. As is apparent from Fig. 1, no solidification occurs where the amount of energy is below a minimal value (e.g. below areas 18, 19 and 22); where the minimal amount of energy penetrates only to a partial depth, partial solidification occurs (e.g. below area 21); where the amount of energy changes abruptly from one value to another, a 90° wall is formed; and, where the amount of energy changes gradually, an inclined wall is created (e.g. below area 20).

In the simplest case of on-off irradiation, if an effective amount of radiation is applied to some areas while none or below the minimal amount to others, a planar object featuring exclusively through-holes and 90° walls is produced.

Additional layers are added to enlarge the object by removing the plate 13, adding more photopolymer on top of

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the object, replacing the same or a different plate 13 and selectively irradiating the uncured photopolymer to obtain an object as seen in Fig. 3A. This process can be repeated many times.

5 When the irradiation is complete, the plate 13 with its coating 23 and mask 15 are slid off and the solidified object 25, with and without the substrate 12 upon which it rests, are taken out of container 10. Excess unsolidified polymer 11 is removed using alcohol, water
10 with detergent or other suitable solvent. The object 25 is dried, for example by using warm air jets, and subjected to additional irradiation, if necessary, to complete the cross-linking. The object 25 can be removed from the substrate 12 either before or after removing
15 unsolidified photopolymer.

 In the embodiment of Fig. 2 all the components are the same except for the substrate 12'. In this apparatus the substrate 12' is transparent and it has a coating 23' similar to 23. In addition, there is a second mask 15'
20 and a second radiation source 24' positioned below the container so that the photopolymer can be irradiated from both above and below. With irradiation from the bottom and no coating 23' on plate 12, the apparatus of Fig. 2 can be used to build an object 25 similarly to the
25 apparatus of Fig. 1.

 The object 25 shown in Fig. 3B can be made by first making the bottom portion 25a, removing plate 13, turning substrate 12 with 25a attached clockwise by angle α , adding photopolymer, replacing plate 13 and irradiating
30 to form portion 25b.

 Although liquid photopolymer is preferred, almost any liquid or sheet polymer that is uncured and can be solidified with radiation can be used in the process. Usually, light-sensitive additives are used to reduce required
35 energy. Common additives are benzophenone derivatives, quinones, benzol, benzoin ethers, and halogenated com-

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pounds. Photopolymer in sheet form also can be used instead of the liquid polymer. A preferred photopolymer liquid for use in the present invention is Magnacryl 2296 made by Beacon Chemical Company of Mount Vernon, New York.

5 A suitable radiation source is an assembly of General Electric lamps emitting UV light in the range of about 200 to about 500 nm, and preferably about 300 nm to about 400 nm, and providing intensity of several mw/cm^2 at the top surface of the photopolymer. Some photopolymers may require different wavelengths and/or radiation intensities. Mercury lamps, lasers, cathode ray tubes or other radiation sources, quartz or other radiation-transmitting materials and different automatically controlled actuators for scanning with an aperture or an optical fiber, also can be used. For high accuracy and resolution the radiation should be collimated.

10 The radiation source can also be one that scans (by deflecting the beams as in CRT or by moving the device 24 and/or container 10) and modulates. As seen in Fig. 4A and 4B, if such a radiation is used there is no need for a mask 15. Substrate 12 is not necessary when no layers have to be added on top of the object 25; the object will adhere to the plate 13. The thickness of the object will be determined by the amount of radiation applied to the top of plate 13 and can be less than the depth of the polymer. Alternatively, a mask can be used to modulate radiation, with or without a scanner, to prepare objects that have a thickness less than the depth of the polymer.

25 The substrate 12 can be of glass, plastic, stainless steel or any other material which will serve as a suitable support to which the solidified object will attach and will not displace when plate 13 is slid off. It can be opaque or transparent as in the case of substrate 12' in the embodiment of Fig. 2.

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The plate 13 can be of any sufficiently rigid, radiation-transmitting material which should preferably exclude air and prevent the surface of the cured photopolymer from forming other than desired shapes. The preferred plate 13 is of glass or similar rigid transparent material; however, it also can be a sufficiently rigid stretched transparent film which possesses the desired properties with or without a coating 23 (23') or just a film of material useful as coating 23. The plate 13 could also be a fused bundle of optical fibers (fiber optic faceplate) with one end of each fiber overlying the fluid and the other provided with an optical switch (shutter) controlling passage of radiation from a radiation source according to commands from a computer so that each fiber irradiates for a prescribed period of time and the top surface of the photopolymer is simultaneously irradiated with proper amount of energy. Currently available faceplates utilizing 8 μm diameter interstitial black fibers called EMA provide image resolution of 16 μm .

To modulate the radiation if a source of uniform radiation is used the mask 15 can be employed. The mask 15 may be of any functionally suitable material and it can be comprised of one or more components. The mask 15 may be a part of plate 13 or a separate item positioned preferably between the plate 13 and coating 23. In a preferred embodiment, mask 15 is a metallic layer on the bottom of plate 13 and is made of microelectronic mask glass.

The transparent coatings 23, 23' can be any material which leaves the irradiated surface of the photopolymer capable of further cross-linking and to which the solidified polymer preferably does not adhere. The preferred material is fluorinated ethylene propylene copolymer, which is available as Teflon FEP in film, adhesive tape and other forms from du Pont of Wilmington, Delaware. It

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may be produced by the copolymerization of tetrafluorethylene and hexafluoropropylene. Another resin that can be used is UHMW polyolefin available from CHR Industries of New Haven Connecticut as an adhesive tape. Other
5 radiation transmitting materials that inhibit photopolymer cross-linking like those containing copper or oxygen can also be employed.

Apparatus where plate 13 seals the container are also possible in which case means are provided to allow free
10 photopolymer flow to make up for shrinkage.

In still another embodiment no coating 23 is used in the apparatus of Fig. 1 if the substrate 12 is made of Teflon or other material the polymer does not adhere to. In this embodiment after irradiation the plate 13
15 with the object attached is slid off the substrate 12 inside the container.

Three-dimensional objects formed by the apparatus of the present invention can be used, in particular, as parts in integrated electric circuit boards. In such
20 case, an insulating medium such as Magnacryl 2296, can be employed to form the structural portion, and the conducting layer can be deposited by metallization with subsequent mask etching, or by another process.

The method of the present invention also can be used
25 to produce more complex objects by building separately a number of three-dimensional portions or slices, that have two surfaces which are capable of further cross-linking and attaching the slices together. They can be then joined by radiation. For best results, it should be done
30 in the absence of oxygen and other inhibitors of cross-linking. The apparatus of the embodiment of Fig. 2 is useful for making such portions or slices as well as the apparatus of Fig. 1 when substrate 12 is made of Teflon or other material preserving cross-linking ability of the
35 polymer. The apparatus of Fig. 4A and 4B having a plate 13, 13' with a coating 23, 23' also can be used.

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Some of the slices or portions may be made from different polymers to provide different mechanical, electrical and other properties. By use of the novel method and apparatus of the present invention, valuable
5 multilayer objects can be made such as integrated electric circuit boards (ECB). An example of such an ECB is shown in Fig. 5 in which 26 is an insulating layer, 27 is a conducting layer, 28 is another insulating layer, 29 is another conductor, 30 is another insulating layer, 31
10 are electrical components and 32 are pins in one or more slices of solidified photopolymer. Electrical components can be inserted before the desired portion or slice is formed, so that the components can get "soldered" at the time of solidification.

15 In the embodiment of Fig. 6 in addition to the components of Fig. 1, guide 33 and drives 35, 36 are employed. Plate 13 is preferably a fiberoptic faceplate that transmits the beam accurately from mask 15 to radiation emitting surface 34. Plate 13 is housed in guide 33
20 which is made of opaque material and isolates side surface of plate 13 from photopolymer both optically and hydraulically. Guide 33 is supported and positioned by drive 35. It is preferable that container 10 is initially filled to have enough photopolymer to form the whole
25 object, and that guide 33 and plate 13 are of sufficient length. Drive 36 provides automated change of mask 15 from one irradiation step to another.

To make an object, plate 13 is immersed in photopolymer 11 so that a photopolymer layer of the
30 thickness of the first layer to be formed is created between layer 23 and substrate 12, and proper radiation is applied. To form the second layer, plate 13 is slid off and repositioned, with proper alignment, so that its distance from substrate 12 is increased by the thickness
35 of the second layer to be formed, mask 15 is changed, if necessary, and radiation reapplied. The procedure is

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repeated for successive layers. If required, additional photopolymer is added to keep the surface 34 from becoming exposed.

5 Masks 15 can be made in a form of a strip or roll of film where masks follow in the order of irradiation. Faceplate 13 can be of cross-section smaller than the object formed in which case slower fabrication area by area takes place. Instead of a mask, an array of
10 miniature individually controlled mirrors or shutters like Texas Instruments' chip incorporating a million mirrors can be employed to modulate irradiation of individual fibers of the faceplate 13. Mask 15 with radiation source 24 can be substituted also with a
15 modulating radiation source that can provide different amounts of radiation to different fibers, such as a scanning radiation source that scans individual fibers of faceplate 13, or an array radiation source 24 that includes a number of individually controlled radiation
20 sources (similar to LED displays) one per fiber or per cluster of fibers.

Fig. 7 shows an embodiment of guide 33 with a modulating radiation source 24 that fits inside radiation guide 33 and is mounted preferably adjacent to layer 23. No plate 13 is employed. Layer 23 can be provided
25 with a radiation transmittant plate of glass or other suitable material for rigidity.

The embodiment of Fig. 8 has all the components of that of Fig. 6, except for the mask 15 and the drive 36. Plate 13 is a single fiber, or bundle, and its
30 cross-section is small - of point size. When it is desired to make a three-dimensional object 25 with the described apparatus, layer 23 is positioned at a small distance from substrate 12, radiation from the light source 24 is transmitted through the optical fiber 13 and
35 layer 23 into the uncured photopolymer 11 to solidify the photopolymer between layer 23 and substrate 12 (a

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"point") and to attach it to substrate 12. Guide 33 is then slid off, repositioned over the area on substrate 12 to be solidified next, and radiation reapplied. The procedure is repeated until the desired three-dimensional object is formed. Points can be solidified in different sequences; for some objects it can be done by layers.

Radiation source 24 can be mounted on top or inside of guide 33. Suitable optical fiber 13 is type Z from Applied Fiberoptics of Southbridge, Massachusetts. A suitable drive 35 is an XYZ-positioning stage or, for automated fabrication, an XYZ-positioning table with motors, motion controllers (all, for example, from Daedal Inc. of Harrison City, Pennsylvania) and computer. Container 10 or substrate 12 can also be provided with drives to take over some positioning from drive 35, to expedite fabrication for irradiation sequences requiring large displacements, e.g. Rotary motion can be used in addition or instead of linear motion. Instead of employing layer 23 that preserves cross-linking capability of irradiated photopolymer, guide 33 (or its irradiating tip) can be made of a material containing copper, oxygen or other ingredients that inhibit photopolymer cross-linking and thus preserve further cross-linking capability and let guide 33 be removed from the solidified photopolymer without distorting it.

Radiation guide 33 that irradiates upwards as shown in Fig. 9 or in any other direction can be used. Also, drive 35 that rotates guide 33 (or its irradiating tip), and thus modulates the space angle of irradiation emitting surface 34, can be employed, in particular, to increase fabrication accuracy of curved and inclined walls. Several guides 33, of same or different sizes and space angles of radiation emitting surface 34, can be used to irradiate different areas or to simultaneously irradiate same area from different sides. The latter is useful, for example, in making of thin walls and shells.

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Guide 33 can be partially filled with radiation transmittant material or be hollow as shown in Fig. 10; it is sealed with a relatively rigid layer 23, and a laser or other radiation source 24 is attached.

5 Radiation source 24 can also be mounted separately and connected to guide 13 with radiation-guiding optics, or, dimensions permitting, be mounted inside guide 33 over layer 23 as shown on Fig. 7.

10 When the cavity of guide 33 in Fig. 10 is of sufficiently small cross-section, such as one used for point by point irradiation, and is filled with air, oxygen or other radiation-transmittant inhibitor of cross-linking, or with alcohol or other solvent of the liquid photopolymer, layer 23 does not have to be
15 employed, since the photopolymer will not enter the cavity, its further cross-linking capability is preserved, and guide 33 does not adhere to the solidified photopolymer. The cavity of guide 33 can be sealed hermetically or filled at its radiation source end with a
20 transmittant material, for example, with optical fibers occupying all but the irradiation tip of the cavity.

Still other advantages and efficiencies of using my method in making such objects will be apparent to those skilled in the art.

25 Those skilled in the art will appreciate that the cross-linkable surfaces of objects made by the desired method lend themselves to easier deposition of electroconductive layers by other manufacturing methods. For example, fine metal powders can be embedded into cross-
30 linkable surfaces by use of jets through masks; the powders will then be permanently secured upon irradiation.

It also is to be understood that the objects made by the present invention can also include alien objects.
35 The photopolymers readily adhere to many materials,

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therefore, objects can be formed in situ by irradiating a liquid photopolymer so it will solidify upon an existing part which serves in this case as the substrate. Special container design may be needed, depending on shape and
5 access to existing assembly.

It further will be understood that porous objects can be made by creating pores in the object by proper use of modulated radiation with or without masks. The pores may be of different sizes and spacing to effect the local
10 density of the object.

While only several preferred embodiments have been shown and described herein, the invention is not intended to be limited thereby but only by the scope of the claims which follow.

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The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. In the method of preparing three-dimensional objects from an uncured photopolymer by treating the photopolymer with radiation to solidify the polymer, the improvement which comprises irradiating said uncured
5 photopolymer by transmitting radiation through a transmittent material in contact with the uncured photopolymer, said material being a material which does not interfere with the solidified photopolymer's ability to subsequently cross-link.

2. The method of claim 1 in which the material is fluorinated ethylene propylene.

3. A method of preparing three-dimensional objects which comprises:

- (a) providing a quantity of an uncured photopolymer;
- (b) placing in contact with said photopolymer a
5 transmittant, relatively rigid member which does not significantly interfere with the subsequent cross-linking of said photopolymer and which can be removed after irradiation; and,
- (c) then transmitting photopolymer solidifying
10 radiation through said relatively rigid member in an amount effective to cause said photopolymer to solidify to the desired extent.

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4. A method of claim 3 in which the relatively rigid member has a transparent coating on its bottom surface, said coating being of a material and which does not significantly interfere with the subsequent cross-linking of the photopolymer.

5. The method of claim 3 which includes the additional steps of:

(d) adding additional uncured photopolymer to cover the solidified photopolymer;

(e) positioning a relatively rigid member as in (b); and

(f) transmitting photopolymer solidifying radiation through the relatively rigid member in an amount effective to cause additional said photopolymer to solidify to the desired extent and to adhere to said solidified photopolymer.

6. The method of claim 3 in which the object of solidified photopolymer is joined to a similarly prepared object by joining the two objects together along surfaces that are capable of further cross-linking, and then irradiating the thus formed combination.

7. A method of claim 3 in which the relatively rigid member is provided with a mask to modulate radiation.

8. A method of Claim 3 in which different amounts of radiation are applied to different areas of the relatively rigid member.

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9. An apparatus for producing of three-dimensional objects from photopolymer, said apparatus comprising:
- (a) quantity of an uncured photopolymer;
 - (b) a radiation transmittant member having a surface adapted to come into contact with the photopolymer;
 - (c) means for preserving subsequent cross-linking capability of the photopolymer; and
 - (d) a source of photopolymer solidifying radiation adapted to transmit an effective amount of radiation through said member into said photopolymer so that at least a portion of said photopolymer will solidify.
10. An apparatus of claim 9 in which the rigid member is provided with a mask to modulate radiation.
11. An apparatus of claim 9 in which the rigid member is a bundle of optical fibers.
12. An apparatus of claim 9 in which the means for preserving subsequent cross-linking is a layer of fluorinated ethylene propylene.
13. An apparatus of claim 9 in which the means for preserving cross-linking is a UHMW polyolefin.
14. An apparatus of claim 9 in which there is a substrate in the container to support solidified photopolymer.

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15. An apparatus of claim 9 in which the source of radiation is capable of delivering different amounts of energy to different areas of the rigid member.

16. An apparatus of claim 9 in which the source of radiation is a source of ultraviolet light.

17. A method of claim 3 in which the substrate is an alien object to which the solidified photopolymer will permanently adhere.

18. In the method of forming a three-dimensional object by the irradiation of a photopolymer, the improvement which comprises providing a quantity of photopolymer, said quantity being thicker than the object
5 to be formed, covering a surface of said photopolymer with a rigid radiation transmitting member, irradiating each area of said member to form an object of the desired thickness in each area.

19. A method of claim 18 in which the radiation is modulated to produce a porous object.

20. A method of claim 5 in which the substrate is tilted to a desired angle before adding additional polymer.

21. A method of claim 3 in which the object made is an integrated electric circuit board.

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22. A method of claim 5 in which the added photopolymer is electrically conductive or insulating.

23. A method of claim 5 in which an electrically conductive material is incorporated into object.

24. A method of producing a three-dimensional object in a container, which comprises irradiating polymer through a radiation transmittant rigid member to cause the polymer to solidify upon a substrate in the
5 container, then sliding the solidified polymer off the substrate while keeping it attached to the rigid member.

25. An apparatus for producing three-dimensional objects from a photopolymer, said apparatus comprising:
 (a) a quantity of an uncured photopolymer; and
 (b) a source of photopolymer solidifying radiation
5 which is capable of varying the amount of radiation it emits to different areas of said photopolymer so that the depth of solidification can be varied in said different areas.

26. An apparatus of claim 9 in which the radiation transmittant member and means for preserving subsequent cross-linking is a single member of a material which is both radiation transmittant and which preserves
5 subsequent cross-linking.

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27. An apparatus of claim 9 in which the means for preserving subsequent cross-linking is a layer of material between the radiation transmittant member and the photopolymer.

28. In a method of preparing three-dimensional objects from an uncured photopolymer by treating the photopolymer with radiation to solidify the polymer, the improvement which comprises irradiating said uncured
5 photopolymer by emitting radiation directly into desired areas inside of said photopolymer.

29. A method of preparing three-dimensional objects which comprises:

- (a) providing a quantity of uncured photopolymer;
- (b) positioning a radiation-emitting surface inside
5 said uncured photopolymer in contact with area of said photopolymer to be irradiated; and
- (c) emitting photopolymer solidifying radiation from said radiation emitting surface in an amount effective to cause photopolymer to solidify to the desired extent.

30. The method of claim 29 in which said radiation emitting surface has a transparent coating, said transparent coating being of material which does not interfere with the subsequent cross-linking of the photopolymer.

31. The method of claim 30 in which said material is fluorinated ethylene propylene.

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32. The method of claim 30 in which said material is UHMW polyolefin.

33. The method of claim 29 in which steps (b) and (c) are repeated desired number of times to form subsequent parts of the object in desired sequence.

34. The method of claim 29 which additionally includes preserving the subsequent cross-linking capability of photopolymer in contact with said radiation emitting surface.

35. An apparatus for producing of three-dimensional objects from photopolymer, said apparatus comprising:

- (a) a quantity of uncured photopolymer;
- (b) a radiation emitting surface adapted to come
5 into contact with desired area inside the photopolymer;
and
- (c) a source of photopolymer solidifying radiation
adapted to transmit an effective amount of radiation
through said radiation emitting surface into said desired
10 area inside the photopolymer so that at least a portion
of said desired area inside photopolymer will solidify.

36. An apparatus of claim 35 which additionally includes means for preserving subsequent cross-linking capability of photopolymer layer adjacent to said radiation emitting surface.

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37. An apparatus of claim 35 in which said radiation emitting surface is of material that preserves subsequent cross-linking capability of photopolymer surface adjacent to said radiation emitting surface.

38. An apparatus of claim 37 in which said material is fluorinated ethylene propylene.

39. An apparatus of claim 37 in which said material is UHMW polyolefin.

40. An apparatus of claim 35 which additionally includes a mask to modulate irradiation of said photopolymer.

41. An apparatus of claim 35 which additionally includes optical fibers to transmit radiation from said source of radiation to said radiation emitting surface.

42. An apparatus of claim 35 in which said means include a material inhibiting cross-linking of said photopolymer.

43. An apparatus of claim 35 which includes means for providing desired mutual space orientation of said radiation emitting surface and said photopolymer.

44. An apparatus of claim 35 which includes an additional radiation emitting surface.

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45. An apparatus of claim 35 in which said source of photopolymer solidifying radiation is a source that is capable of providing varying amounts of radiation across said radiation emitting surface.

46. An apparatus of claim 40 which additionally includes means for the automated changing of said mask.

47. An apparatus of claim 35 wherein said radiation emitting surface is small to permit forming said object point by point.

48. The method of claim 33 wherein said radiation-emitting surface is small to permit forming said object point by point.

49. In the method of preparing three-dimensional objects from an uncured photopolymer by treating the photopolymer with radiation to solidify the photopolymer, the improvement which comprises irradiating said uncured photopolymer in contact with irradiation means, said irradiation means being means that preserve the solidified photopolymer's ability to subsequently cross-link.

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50. A method of preparing three-dimensional objects which comprises:

(a) bringing into contact a quantity of an uncured photopolymer and irradiation means that preserve
5 subsequent cross-linking capability of said photopolymer and which can be removed after irradiation; and,

(b) then transmitting photopolymer solidifying radiation through said irradiation means in an amount effective to cause said photopolymer to solidify to the
10 desired extent.

51. The method of claim 50 which includes the additional steps of:

(c) repeating step (a) for additional uncured photopolymer that is added to cover the solidified
5 photopolymer;

(d) transmitting photopolymer solidifying radiation through the irradiation means in an amount effective to cause additional said photopolymer to solidify to the desired extent and to adhere to said solidified
10 photopolymer.

52. An apparatus for producing of three-dimensional objects from photopolymer, said apparatus comprising:

(a) quantity of an uncured photopolymer;
(b) irradiation means adapted to come into contact
5 with the photopolymer;

(c) means for preserving subsequent cross-linking capability of the photopolymer; and

(d) a source of photopolymer solidifying radiation adapted to transmit an effective amount of radiation
10 through said irradiation means into said photopolymer so that at least a portion of said photopolymer will solidify.

[received by the International Bureau on 05 August 1988 (05.08.88)
original claims 4,10,11,15,17,19 and 20 amended; new claims 53-56 added (6 pages)]

4. A method of claim 3 in which the relatively rigid member has a transparent coating on its bottom surface, said coating being of a material which does not significantly interfere with the subsequent cross-linking of the photopolymer.

5. The method of claim 3 which includes the additional steps of:

(d) adding additional uncured photopolymer to cover the solidified photopolymer;

(e) positioning a relatively rigid member as in (b); and

(f) transmitting photopolymer solidifying radiation through the relatively rigid member in an amount effective to cause additional said photopolymer to solidify to the desired extent and to adhere to said solidified photopolymer.

6. The method of claim 3 in which the object of solidified photopolymer is joined to a similarly prepared object by joining the two objects together along surfaces that are capable of further cross-linking, and then irradiating the thus formed combination.

7. A method of claim 3 in which the relatively rigid member is provided with a mask to modulate radiation.

8. A method of Claim 3 in which different amounts of radiation are applied to different areas of the relatively rigid member.

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9. An apparatus for producing of three-dimensional objects from photopolymer, said apparatus comprising:

(a) quantity of an uncured photopolymer;

(b) a radiation transmittant member having a surface adapted to come into contact with the photopolymer;

(c) means for preserving subsequent cross-linking capability of the photopolymer; and

(d) a source of photopolymer solidifying radiation adapted to transmit an effective amount of radiation through said member into said photopolymer so that at least a portion of said photopolymer will solidify.

10. An apparatus of claim 9 in which the radiation transmittent member is provided with a mask to modulate radiation.

11. An apparatus of claim 9 in which the radiation transmittent member is a bundle of optical fibers.

12. An apparatus of claim 9 in which the means for preserving subsequent cross-linking is a layer of fluorinated ethylene propylene.

13. An apparatus of claim 9 in which the means for preserving cross-linking is a UHMW polyolefin.

14. An apparatus of claim 9 in which there is a substrate in the container to support solidified photopolymer.

15. An apparatus of claim 9 in which the source of radiation is capable of delivering different amounts of energy to different areas of the radiation transmittent member

16. An apparatus of claim 9 in which the source of radiation is a source of ultraviolet light.

17. A method of claim 3 in which said quantity of uncured photopolymer is provided on a substrate and the substrate is an alien object to which the solidified photopolymer will permanently adhere.

18. In the method of forming a three-dimensional object by the irradiation of a photopolymer, the improvement which comprises providing a quantity of photopolymer, said quantity being thicker than the object to be formed, covering a surface of said photopolymer with a rigid radiation transmitting member, irradiating each area of said member to form an object of the desired thickness in each area.

19. A method of claim 3 or 18 or 29 or 50 in which the radiation is modulated to produce a porous object.

20. A method of claim 5 in which said quantity of uncured photopolymer is provided on a substrate and the substrate is tilted to a desired angle before adding additional polymer.

21. A method of claim 3 in which the object made is an integrated electric circuit board.

45. An apparatus of claim 35 in which said source of photopolymer solidifying radiation is a source that is capable of providing varying amounts of radiation across said radiation emitting surface.

46. An apparatus of claim 10 or 40 which additionally includes means for the automated changing of said mask.

47. An apparatus of claim 35 wherein said radiation emitting surface is small to permit forming said object point by point.

48. The method of claim 33 wherein said radiation-emitting surface is small to permit forming said object point by point.

49. In the method of preparing three-dimensional objects from an uncured photopolymer by treating the photopolymer with radiation to solidify the photopolymer, the improvement which comprises irradiating said uncured photopolymer in contact with irradiation means, said irradiation means being means that preserve the solidified photopolymer's ability to subsequently cross-link.

53. An apparatus for producing of three-dimensional objects from photopolymer, said apparatus comprising:

- (a) a quantity of uncured photopolymer in a container;
- (b) a substrate in said container upon which said object is to be produced;
- (c) means for changing thickness of said photopolymer on said substrate by displacing said container relative to said substrate; and
- (d) a source of photopolymer solidifying radiation.

54. An apparatus for producing three-dimensional objects from a photopolymer, said apparatus comprising:

- (a) a quantity of uncured photopolymer;
- (b) an array of sources of photopolymer solidifying radiation; and
- (c) means for controlling said sources to provide a combined irradiation of said quantity of uncured photopolymer according to configuration of said object.

55. An apparatus for producing three-dimensional objects from a photopolymer, said apparatus comprising:

- (a) a quantity of uncured photopolymer;
- (b) a source of photopolymer solidifying radiation ;
- (c) an array of shutters; and
- (d) means for controlling opening and closing of said

shutters to provide a combined irradiation of said quantity of uncured photopolymer according to configuration of said object.

56. An apparatus for producing three-dimensional objects from a photopolymer, said apparatus comprising:

- (a) a quantity of uncured photopolymer;
- (b) a source of photopolymer solidifying radiation;
- (c) an array of mirrors; and
- (d) means for controlling position of said mirrors to provide a combined irradiation of said quantity of uncured photopolymer according to configuration of said object.

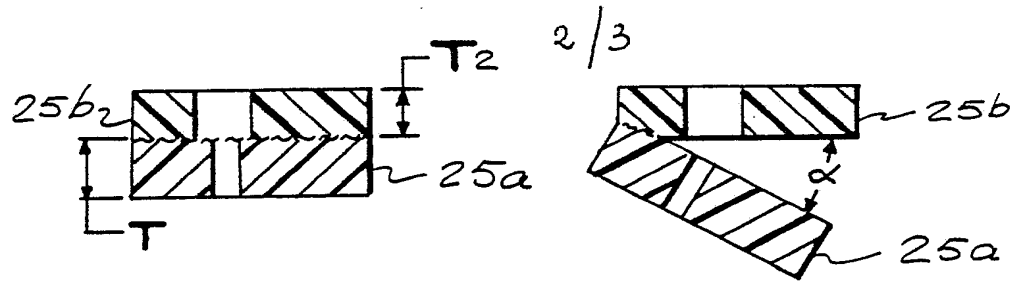


FIG. 3A

FIG. 3B

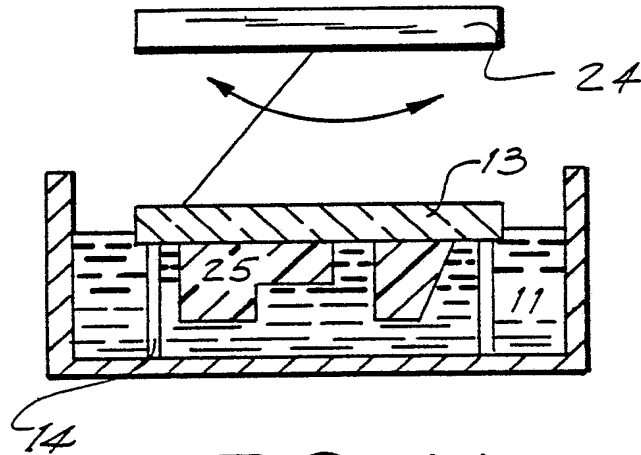


FIG. 4A

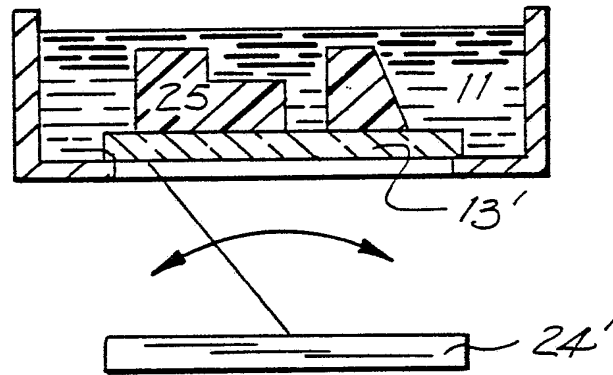


FIG. 4B

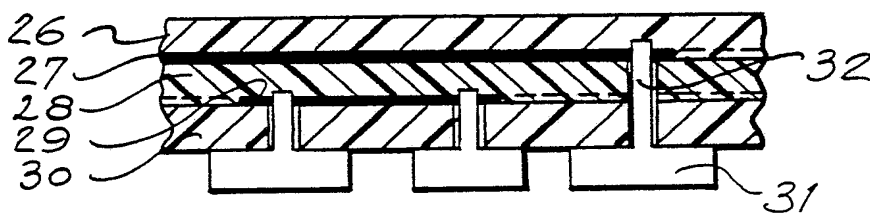


FIG. 5

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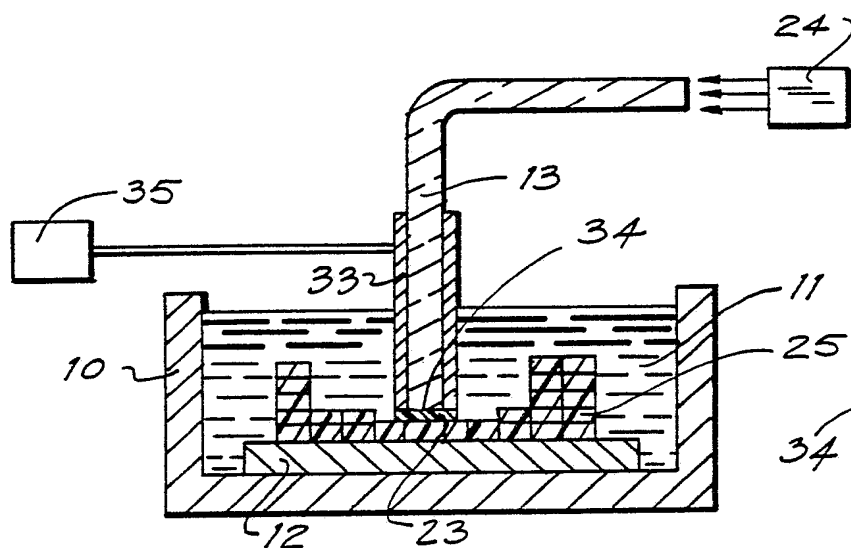


FIG. 8

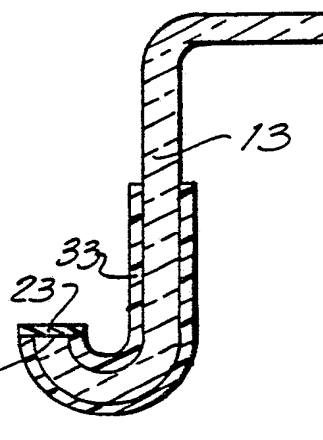


FIG. 9

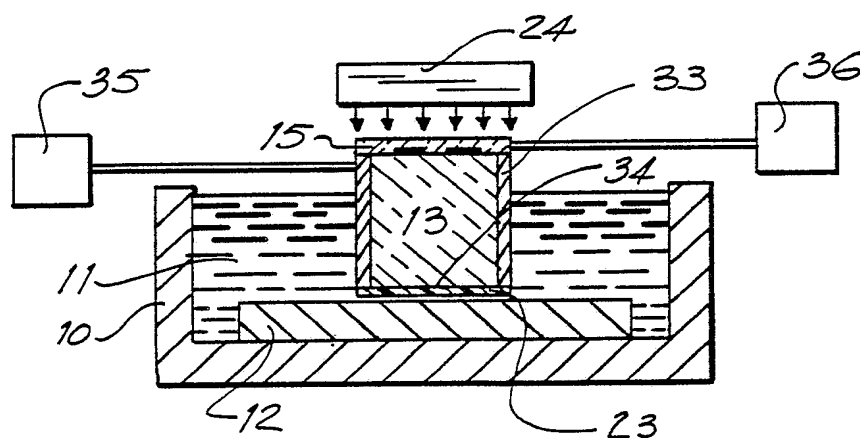


FIG. 6

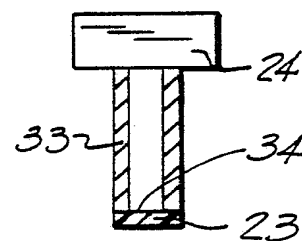


FIG. 10

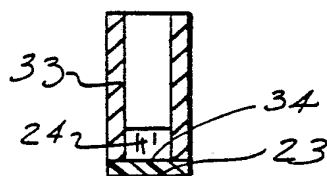
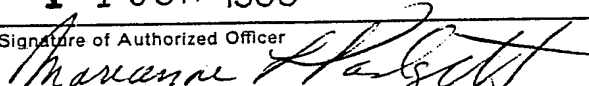


FIG. 7

INTERNATIONAL SEARCH REPORT

PCT/US88/00502

International Application No.

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) ⁶		
According to International Patent Classification (IPC) or to both National Classification and IPC IPC(4): B05D 3/06; B29C 35/08; B29B 13/08 US. Cl. 427/54.1; 264/22; 425/174		
II. FIELDS SEARCHED		
Minimum Documentation Searched ⁷		
Classification System	Classification Symbols	
U.S.	427/54.1; 430/321; 425/ 174, 174.4, 174.6, 67, 69 264/1.4, 1.5, 1.7, 2.3, 2.4, 22	
Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched ⁸		
Examiner's photo deposition digest		
III. DOCUMENTS CONSIDERED TO BE RELEVANT ⁹		
Category *	Citation of Document, ¹¹ with indication, where appropriate, of the relevant passages ¹²	Relevant to Claim No. ¹³
A	SU,A 626,967 (Kharitonov) 12 Sept. 1978 See Abstract and drawings	1-27, 49-52
A	SU,A 626,968 (Kharitonov) 12-Sept. 1978 See Abstract and drawings	1-27, 49-52
A	JP,A 60-260125 (Hatachi) 23 Dec. 1985	28-48
Y	Mechanical Engineering, Sept/1985 (Fudim), "A New Method of Three-Dimensional Micromachining" pages 54-59	1-27, 49-52
Y	Machine Design, 06 March/1986 (Fudim) "Sculpting Parts with Light" pages 102-106	1-52
<div style="display: flex; justify-content: space-between;"> <div style="width: 45%;"> <p>* Special categories of cited documents: ¹⁰</p> <p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier document but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p> </div> <div style="width: 45%;"> <p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.</p> <p>"&" document member of the same patent family</p> </div> </div>		
IV. CERTIFICATION		
Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report	
05 May 1988	14 JUN 1988	
International Searching Authority	Signature of Authorized Officer	
ISA/US	 Marianne L. Padgett	

III. DOCUMENTS CONSIDERED TO BE RELEVANT (CONTINUED FROM THE SECOND SHEET)

Category *	Citation of Document, with indication, where appropriate, of the relevant passages	Relevant to Claim No
A.	US,A 4,575,330 (Hull) 11 March 1986 See entire document.	1-52
A	US,A 4,376,160 (Evanchuk) 08 March 1983 See entire document.	1-52
A	US,A 4,228,232 (Rousseau) 14 Oct. 1980 See entire document.	1-52
A	US,A 4,174,218 (Pohl) 13 Nov. 1979 See entire document.	1-52
A	US,A 4,137,081 (Pohl) 30 Jan. 1979 See entire document.	1-52